1. OVERVIEW OF THE FACILITY

LBNL is pursuing design studies and the scientific program for a facility dedicated to the production of x-ray pulses with ultra-short time duration for application in dynamical studies of processes in physics, biology, and chemistry. The proposed x-ray facility has the short x-ray pulse length (~60 fs FWHM) necessary to study very fast dynamics, high flux (up to approximately 10^{11} photons/sec/0.1%BW) to study weakly scattering systems, and tuneability over 1-12 keV photon energy. The hard x-ray photon production section of the machine accomodates seven 2-m long undulators. This is the aspect of the machine that is the subject of the present report. Design studies for longer wavelength sources, using high-gain harmonic generation, are in progress, and will be the subject of future reports.

The x-ray pulse repetition rate of 10 kHz is matched to studies of dynamical processes (initiated by ultra-short laser pulses) that typically have a long recovery time or are not generally cyclic or reversible and need time to allow relaxation, replacement, or flow of the sample.

Synchronization of x-ray pulses to sample excitation signals is expected to be approximately 50 - 100 fs. Techniques for making use of the recirculating geometry to provide beam-based seed and timing signals from early passes through the machine are being studied.

X-rays in the 1 - 12 keV photon energy range are produced by spontaneous emission in tuneable undulators, and will be linearly polarized. Figure 1-1 shows the photon flux (photons per second per 0.1% bandwidth) for the case of a 1 nC bunch at 10 kHz repetition rate, at 2.5 GeV. Up to eleventh harmonic of undulator radiation is shown. Development of the rf photocathode gun to achieve higher charge per bunch will result in greater flux.

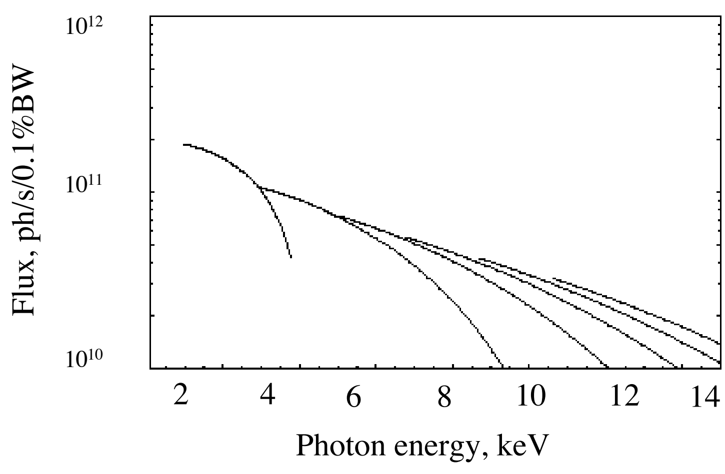

Figure 1-1 Average flux as a function of photon energy.

The major components and systems of the machine are an rf photo-injector, a linear pre-accelerator, a main linear accelerator, magnetic arcs and straight sections, deflecting cavities, a hard x-ray photon production section, and a beam dump [1]. The layout for this baseline configuration is shown in Figure 1-2.

Electron pulses of approximately 20 ps duration and 1-3 nC charge are produced in a high-brightness rf photocathode gun and accelerated to 10 MeV. As described in Chapters 5-RF Photocathode Gun and 8-Flat Beam Adapter, application of a solenoidal magnetic field on the cathode, followed by a specially configured skew-quadrupole channel, allows production of a *flat* beam with *x*/*y* emittance ratio > 50:1 and vertical normalized emittance less than 1 mm-mrad [1]. This principle has been successfully demonstrated at the Fermilab/NICADD Photoinjector Laboratory (FNPL) [2], and LBNL has joined the experiment collaboration to help further work in this regard. Further details may be found in Chapter 7-Experimental Studies at FNPL.

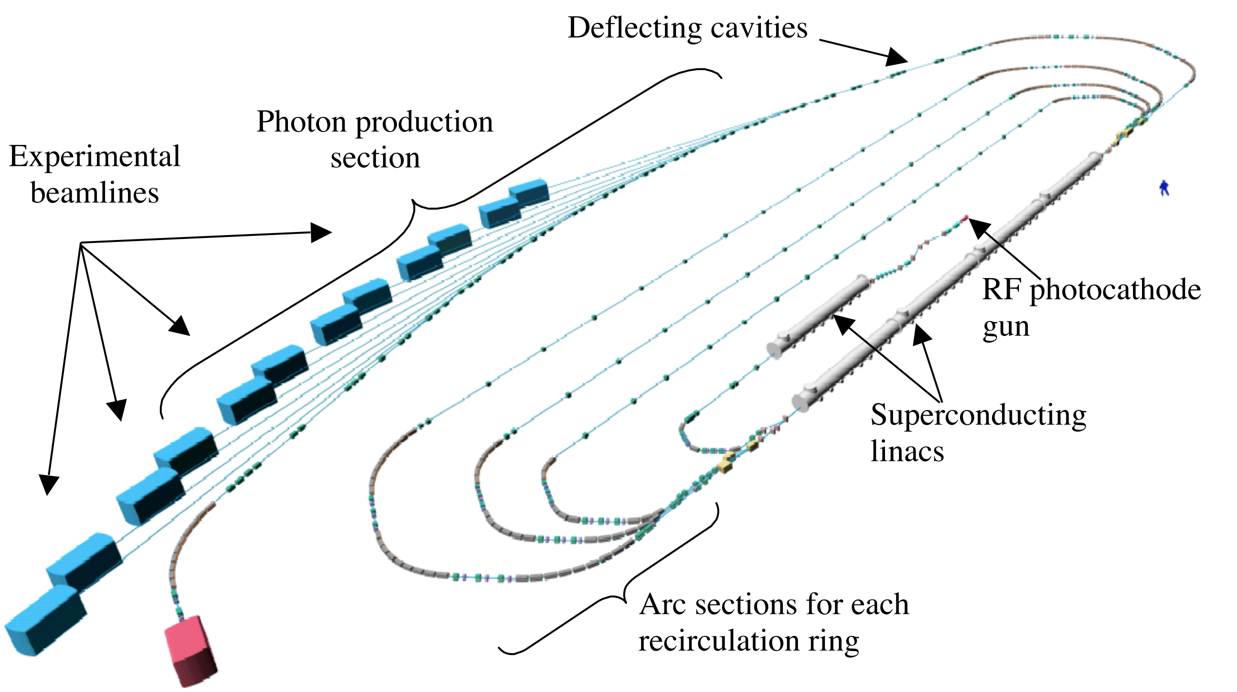

Figure 1-2. Machine layout for the baseline configuration. The beam generated at the rf photocathode gun travels through the injector linac, main linac, transport arcs, deflecting cavities, and photon production section, to the beam dump. The machine footprint is approximately 150 m x 50 m. Both undulator and bend magnet beamlines are shown here.

The electron bunches from the rf gun are further accelerated in a superconducting linear pre-accelerator to 120 MeV. Following this injector linac, the beam passes through a higher-harmonic accelerating structure, which is designed to condition the correlated energy spread in the bunch to prepare for compression from 20 ps to 2 ps. After compression in a 180° arc the beam is transported to the entrance of the recirculating linear accelerator.

In the recirculating linac the final energy of ~2.5 GeV is achieved after four passes through the 600 MeV, 1.3 GHz superconducting rf structure. At the exit of the final arc the electron bunches receive a time-correlated vertical kick in a dipole-mode rf cavity. This imparts to the electron bunch a transverse momentum that is correlated in amplitude to longitudinal position within the bunch. The electrons then radiate x-rays in the downstream chain of undulators and dipole magnets, imprinting this correlation in the geometrical distribution of the x-ray pulse, see Figure 1-3. The correlated x-ray pulse is then compressed by use of asymmetrically cut crystal optics to achieve the ultra-short photon pulse length as described in Chapter 18-Beamlines [3]

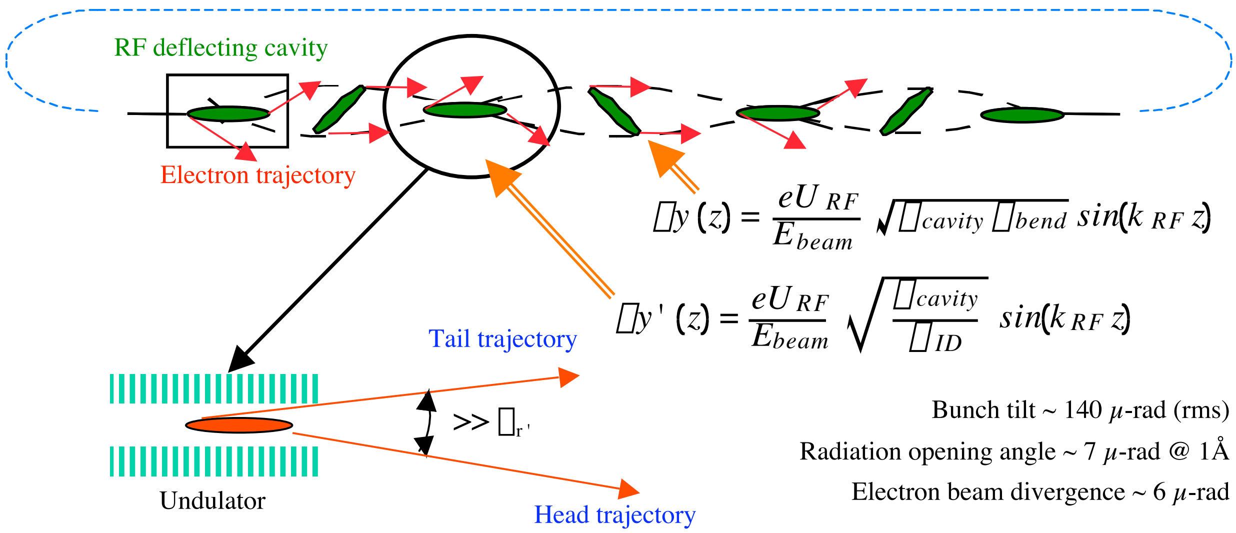

Figure 1-3. Time/position/angle correlation of the electron bunches. By providing divergence larger than the radiation opening angle, or beamsize greater than the diffraction limited size, optical elements can be used to compress the radiation from a bunch [3]. The resultant x-ray pulse length may then be limited by the electron bunch emittance.

The reason for producing a beam with large x/y emittance ratio may now be seen. The electron bunch must be sheared by the action of the deflecting cavity, such that the time duration of a slice of the bunch is short compared to the total bunch length. Figure 1-4 illustrates the principle.

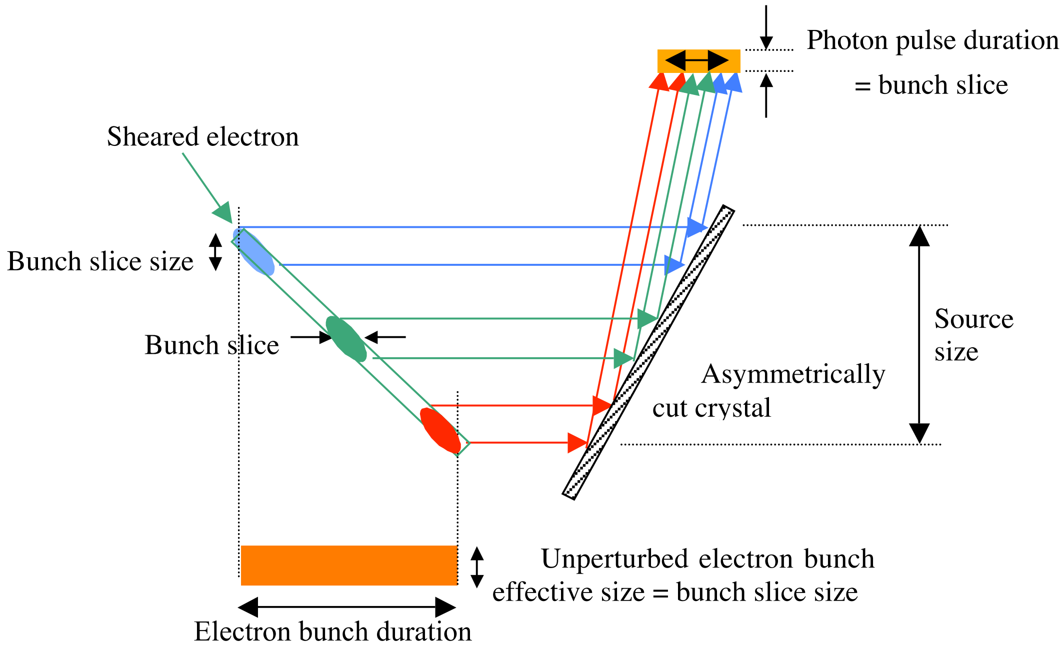

Figure 1-4 Compression of the x-ray pulse. The electron bunch, sheared following the transverse kick applied in the deflecting cavities, is represented as the source of x-rays, with three "slices" of the bunch indicated in different colors. Each slice has a longitudinal dimension determined by the unperturbed electron bunch transverse dimension, the diffraction-limited radiation source size, and the magnitude of the deflection of the bunch.

For significant deflection of the bunch, the x-ray pulse duration $\square_{x\text{-ray}}$ (or slice duration) may be written in terms of the electron bunch length $\square_l$, the source size presented by the perturbed bunch $\square_{source}$, and the unperturbed electron bunch effective size $\square_{bunch\ effective}$:

$$\frac{\square_{x\text{-}ray}}{\square_{bunch effective}} = tan\frac{\square_l}{\square_{source}} \;\square\; \frac{\square_l}{\square_{source}} \tag{1}$$

The source size is described by the lattice optics and the deflecting cavity voltage U_{RF}

$$\square_{source} = \frac{e\,U_{RF}}{E} sin\left(k_{RF}\square_l\right)\sqrt{\square_{cavity}\square_{source}} \tag{2}$$

The effective electron bunch size due to the beamsize and the diffraction limited image size is

$$\square_{bunch effective} = \sqrt{\square^2_{beamsize} + \square^2_{radiation}} \tag{3}$$

then the x-ray pulse duration is expressed as

$$\square_{x-ray}\,\square\,\frac{E}{e\,U_{RF}\,k_{RF}}\,\frac{\square_{beamsize}}{\sqrt{\square_{cavity}\square_{source}}}\sqrt{1+\left(\frac{\square_{radiation}}{\square_{beamsize}}\right)^2} \tag{4}$$

A similar expression may be derived for radiation from a diverging source. For short wavelengths, at a given deflecting voltage, the x-ray pulse length is limited by the electron beam emittance. For long wavelengths, the radiation diffraction limited source size dominates and the x-ray pulse length is increased.

Figure 1-5 shows the dependence of x-ray pulse duration (plotted as full-width at half maximum) as a function of the x-ray photon energy for three deflecting cavity voltages and baseline parameters (beta-function at the cavities β_{RF} = 90 m beta-function at the insertion devices $\beta_{undulator}$ = 2 m, beam energy E = 2.5 GeV, beam emittance ε = $9.8\text{x}10^{-11}$ m, and rf wavenumber k = 82 m^{-1}).

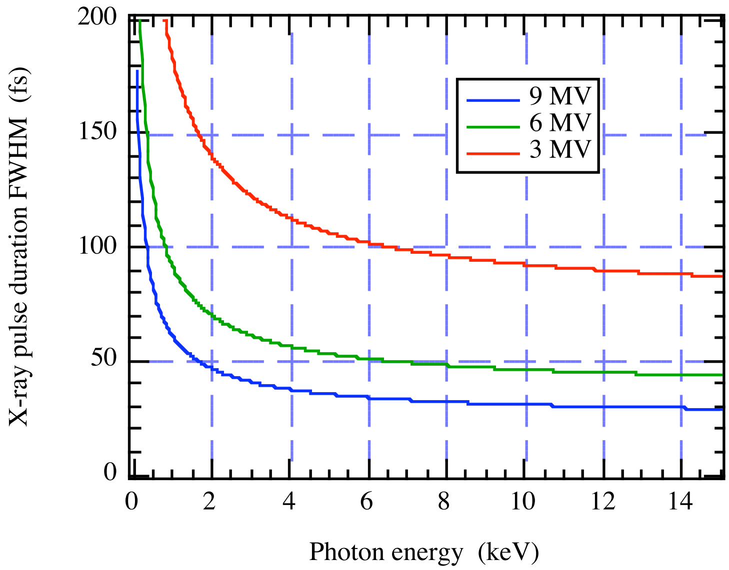

Figure 1-5 X-ray pulse length as a function of photon energy, for three values of deflecting rf voltage.

For baseline operation at 25 kW beam power, the arc returning the 2.5 GeV beam to the linac is not required, and the beam will be taken to a shielded dump as described in Chapter 20-Beam Dump. The option for energy recovery in the linacs be maintained for operations with increased beam power.

The machine lattice is described in Chapter 3-Accelerator Physics, and our studies demonstrate that the lattice can be made to preserve beam transverse and longitudinal emittance [4]. Emittance control and understanding and mitigation of collective effects is critical to a successful machine design, and we are addressing key aspects of accelerator physics involved in beam break-up coherent synchrotron radiation, the influence of resistive wall wakefields, and other effects as described in Chapter 4-Collective Effects [5]. To preserve the six-dimensional emittance through the machine, high-quality instrumentation and diagnostics systems will be required. Techniques for measurement of beam parameters are described in Chapter 16-Beam Diagnostics.

Longitudinal dynamics have been modeled from the rf gun through the injector linac and all passes of the main linac, and emittance dilution due to non-linearities in the rf waveform have been assessed. In the injector, harmonic cavities will be used to linearize the longitudinal phase-space. Chapter 3-Accelerator Physics describes this manipulation of longitudinal phase-space. The bunch lengths and beam pipe apertures under current consideration result in a regime in which the coherent synchrotron radiation impedance may be significant in the lowest energy arcs of the machine, and studies of such effects are reported in Chapter 4-Collective Effects. A smaller beam pipe aperture is beneficial in shielding coherent synchrotron radiation, but the minimum aperture appears to be limited by transverse wakefields arising from the resistive wall impedance.

Conventional photocathode rf guns employ a half-length pillbox cell for the cathode cavity followed by a full cell for rapid acceleration of emitted electrons, and operate in the 10 Hz pulse repetition frequency range. For CW or high duty factor operation, thermal limitations will likely prevent such a design from operating at sufficiently high gradient. We have produced a conceptual design with optimized cavity geometry to allow cooling of the cavity surfaces, and operation at high gradient and high repetition rate [6]. In this design the first cell is modified by the inclusion of a re-entrant nose-cone, on the end face of which the photo-cathode is mounted. This nose-cone serves two purposes: it increases surface area to reduce deposited power density and it enhances the accelerating electric field at the cathode. The design is further described in Chapter 5-RF Photocathode Gun.

The high-brightness electron source must be carefully optimized to minimize and preserve the beam emittance, particularly against deleterious effects of space-charge. We have begun optimization of electron launch phase, rf cavity conditions, and magnetic focussing channels to produce a low-emittance beam. Several simulation codes have been used in this study, as described in Chapter 6-Beam Dynamics in the rf Gun.

Our linac design is based on superconducting rf technology developed for the TESLA project [7]. Identical cryomodules are used for the main linac and the injector linac. Our design considerations here are for a peak accelerating gradient of 20 MV/m in the main linac. The pulse repetition time of 100 μs is less than the superconducting cavity filling time, and the linacs must operate in CW mode. The rf power requirement for the linacs is dominated by the need to overcouple to provide bandwidth necessary for feedback systems to maintain phase and amplitude control against cavity detuning by microphonics. Approximately 8 kW rf power is required per cavity, assuming a bandwidth of 40 Hz. The total linac rf power requirement is approximately 300 kW. Chapter 9-Superconducting RF Linacs describes the design considerations, and Chapter 11-Linac RF Systems describes the power requirements.

The heat dissipated in the power coupler and the cavity helium bath is approximately 100 times greater than for TESLA operations, however an analysis indicates that with additional connections from the supply line to the helium bath for each cavity we may operate at these levels, Chapter 13-Cryogenics describes the refrigeration and cryogenics transport systems.

3.9 GHz superconducting cavities provide the deflecting voltage along the bunch, and rf designs for 7-cell cavities operating in a hybrid TM/TE mode are described in Chapter 10-Deflecting Cavities. Seven such cavities will be required to provide a deflecting voltage of up to 8.5 MV, allowing for operations at the higher beam energy of 3.1 GeV [8].

Several narrow-gap in-vacuo superconducting undulator designs have been characterized as high-flux sources and are summarized in Table 1-1. The machine design accommodates an energy increase to 3.1 GeV, and in that case the flux of 10 keV photons from 1 nC bunches at 10 kHz may be increased to 5.6×10^{10} photons/sec/0.1%BW. We also envisage development of photocathode gun performance to reach 3 nC per bunch, resulting in $\sim 10^{7}$ photons/pulse at 10 keV.

Synchronization and timing of the ~60 fs x-ray pulse to the experimental excitation pulse is critical to studies of ultra-fast dynamics. For our scheme of bunch manipulation followed by x-ray pulse compression we find that the phase jitter of the deflecting cavities with respect to the experimental laser pulse dominates timing issues [9]. We propose to derive all accelerator rf signals from phase-locked laser oscillators. The rf gun, linacs, and deflecting cavities are thus phase-locked to the experimental pump lasers, and timing jitter between the optical laser and the x-ray pulse emitted by the beam is minimized. Phase and amplitude feedback of the deflecting cavities is expected to provide x-ray pulse to laser pulse stability of better than 100 fs. These techniques are described in Chapter 19-Synchronization.

Table 1-1 Average flux for three in-vacuo undulator designs, 1 nC bunches at 10 kHz rate

Period	Gap	Peak magnetic field	Kmax	Flux at 2 keV 2.5/3.1 GeV	Flux at 10 keV 2.5/3.1 GeV
mm	mm	T		10^{10} photons/sec/0.1%BW	
20	5	1.5	2.8	8 / 11.4	1.1 / 2.7
14	5	1.5	2.0	15.6 / 17.8	2.3 / 4.5
14	3	2.0	2.6	15.6 / 17.8	3.4 / 5.6

Laser systems will be an integral part of the machine, providing stable timing and synchronization signals, as well as the electron source through the photocathode laser, and the experimental pump lasers. Laser systems are described in Chapter 17.

Lattice magnets are of conventional water-cooled electromagnet design, with the exception of a few specialized magnets in the beam spreader and combiner regions adjacent to the main linac. In these compact regions special septum magnets are employed, dipoles which act on beams of differing energy, and small quadrupole designs in order to act on separate orbits of beams at different energies. Chapter 14-Magnets describes the designs.

The vacuum systems are less demanding than typical storage rings due to the much reduced outgassing from a relatively small average beam current, and the modest lifetime requirements of a pulsed machine. Chapter 15-Vaccum Systems presents an analysis of requirements.

Conventional facility requirements for the proposed facility are presented in Chapter 21. Issues in selecting a local site for the facility are discussed in Chapter 22-Site Selection.

Chapter 2 describes trade studies made to arrive at the baseline configuration presented here. Chapter 23 presents an analysis of the most significant risk factors.

Table 1-2 Major baseline design parameters

Bunch charge	1 nC (goal 3 nC)
Bunch repetition rate	10^4 Hz
Beam energy in photon production section	2.5 GeV
Beam energy spread at 2.5 GeV	200 keV
Bunch length in photon production section	2 ps (full length)
Electron tilt angle in the undulator	0.14 mrad
RF deflection cavity frequency	3.9 GHz
RF deflection cavity transverse voltage	8.5MV
Undulator length	2 m
Bunch length at gun exit	20 ps
Normalized emittance from gun	3×10^{-6} m-rad
x/*y* normalized emittance from flat-beam transformer	$20 / 0.4 \times 10^{-6}$ m-rad
Beam energy spread from gun	± 20 keV
Energy gain per pass in main linac	600 MeV

The configuration described in the present report is concerned primarily with the production of hard x-ray's. In addition, conceptual design studies for producing high-flux, short-pulse photons at lower photon energies are in progress. Of particular interest is the technique of high-gain harmonic generation [10]. The scheme is shown in Figure 1-6. A high-brightness electron beam is accelerated to ~2.5 GeV, and passed through an undulator where a seed laser modulates the charge over a short length of the bunch. This modulation is then amplified in a following undulator, tuned to a higher harmonic of the seed laser. The electron pulse may then be delayed in a short chicane, and the process repeated by modulating the beam this time with the harmonic radiation produced in the previous undulator.

This technique allows variable flux, up to 10^{12} photons per pulse, and possibly up to keV photon energies. Details of this scheme will be reported in future publications.

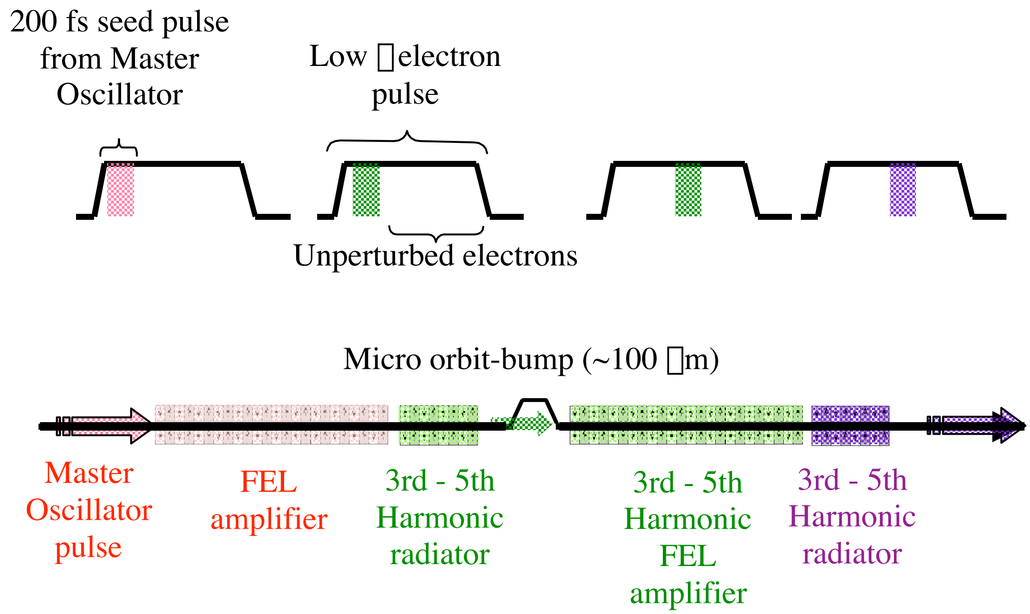

Figure 1-6 UV and soft x-ray production technique using high-gain harmonic generation.

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